Data Communication in Electromagnetic Nano-networks for Healthcare Applications

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Abstract. One of the most promising applications of nanotechnology is their use in health care scenarios to monitor, in real-time, several parameters inside the human body such as cancer biomarker detection, glucose level, etc. However, real-time medical parameters communication is constrained by the tiny size of nano-nodes and their extremely limited energy. Ongoing efforts in this area are in their very early stage of development. Therefore further research is required to propose a suitable communication model. In this paper, we study the deployment of nano-networks in a living biological environment, and we focus on communication protocols challenges that must be overcome. We also proposed a multi-hop data dissemination approach that transmits sensed data from nano-nodes moving inside an artery to an outside controller while optimizing energy consumption.

Keywords: Nano-network · Healthcare applications · Electromagnetic communication · Communication protocols

1 Introduction

Nanotechnology is undoubtedly an emerging technology that will have a major impact in our daily lives in the near future. According to the famous scientist Robert Floyd Curl Jr, winner of the Nobel Prize in Chemistry in 1996, nanotechnology has been used for two thousand years.

Recently, because of the growing interest in atomic and subatomic particles, the scientific community has begun to question the viability of a deterministic disposition of these nano-particles. As a result, nano-science has taken off and many sub-disciplines are now focusing their efforts on assembling nano-particles to produce much more qualified nano-materials and nano-devices.

A nano-network is formed by connecting nano-devices; therefore, it is able to perform more complex tasks such as drug administration, health surveillance and the detection of biological or chemical attacks in nano-scale environments through the cooperation of nano-machines. Nano-networks connected to Internet

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gateways enables a new network paradigm called *Internet of Nano-Things* or IoNT.

The IoNT has a great potential for advanced health services and applications. Integration of IoNT with other healthcare network systems will expand the range of services that can be provided to patients as well as health decision-makers. But the efficient dissemination of data in a nano-network poses several challenges to communication protocols.

The main contribution of this paper, is to study the applicability of the evolving nano-network technology for heathcare monitoring from a communication protocols perspective. Nano-communication challenges in healthcare applications are identified and the main architecture of our energy efficient communication approach is presented.

The reminder of this paper is organized as follows: In Sect. 2, we define some nanotechnology related concepts. Then, Sect. 3, presents the communication challenges related to the application of nanotechnology in healthcare applications and details recent proposed communication protocols. The proposed architecture is presented in Sect. 4. Finally, concluding remarks are given in Sect. 5.

2 An Overview of Nano-network Architecture

The concept of nanotechnology was described in detail by the physicist Richard Feynman in his famous lecture entitled *"There is a lot of room for substance"* in 1959. The development of nanotechnologies has a considerable potential for advances in knowledge and positive transformations in our daily lives. Some examples of the benefits they can bring are: New medical diagnostic tools, better targeted drugs to combat cancer tumors or other serious illnesses such as AIDS, technological leaps with new breakthroughs in information and communication technologies, materials that are both stronger, more resilient and better formable or deformable, openness to substantial progress in the area of energy savings and new energies that will condition our future, etc.

The progress of nanotechnology improves the development of new nano-materials that is known in literature as *nano-machine*. Throughout this paper, we use the terms '*nano-machine*', and '*nano-device*' interchangeably. The size of these nano-machines ranges from one to few hundred of nano-meters and they can perform only simple computation, sensing and actuation tasks. A network of nano-machines is called a *nano-network*. This later expands the capabilities of a single nano-device by providing a way to cooperate and share information. Finally, *nano-communication* is defined as the exchange of information at the nano-scale on the basis of any wired or wireless interconnection of nano-machines in a nano-network.

2.1 Different Components of a Nano-machine

A nano-machine is an integrated device formed of one or more components incorporated into each other in different levels of complexity. It ranges from a simple

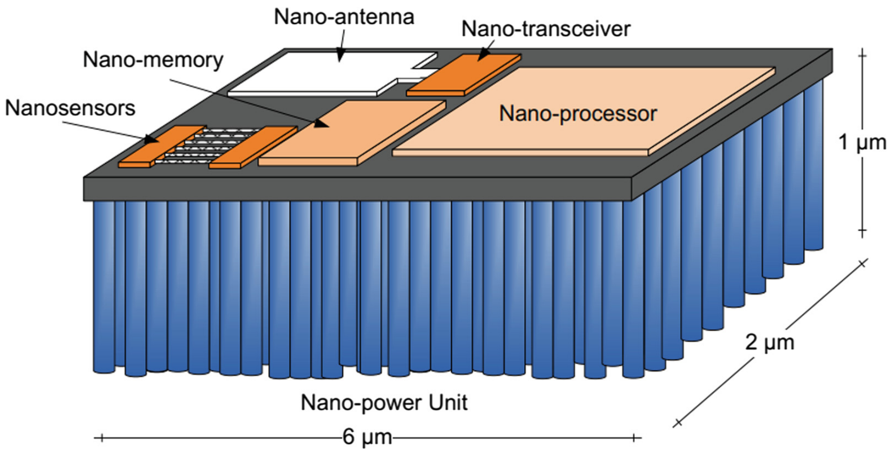

Fig. 1. Nano-machine units [2]

miniaturization machine to high-end and sophisticated nano-robotics. As shown in Fig. 1, a Nano-machine is composed by the following units [2]:

– **Processing unit:** Nano-processors are activated by the development of smaller FET transistors in different forms. The smallest transistor experimentally tested to date is based on a thin graphene strip. Despite being small, the transistors are able to operate at higher frequencies.
– **Data storage unit:** Nano-memories store a single bit on a single atom by nano-material and new technologies. The atomic memories have been currently introduced which consider the presence of one silicon atom as storing bit 1 (or 0) and its absence as storing bit 0 (or 1).
– **Power unit:** The supply of nano-machines requires new types of nano-batteries [16,17] as well as nano-scale energy recovery systems [18]. One of the most promising techniques is to convert vibratory energy into electricity. This energy can then be stored in a nano-battery and consumed dynamically by the device.
– **Communication unit:** Nano-antennas units together with transceiver schemes will enable the communication among nano-devices.
– **Sensing unit:** A nano-sensor is not just a tiny sensor, but a device that makes use of the novel properties of nano-materials to identify and measure new types of events in the nano-scale, such as the physical characteristics of structures just a few nano-meters in size, chemical compounds in concentrations as low as one part per billion, or the presence of biological agents such as virus, bacteria or cancerous cells. Those tiny sensors can be classified into three types which are *physical*, *chemical* and *biological* nano-sensors and they have been developed by using graphene and other nano-materials [15,19]. Nano-sensors types will be detailed in the following sub-section.

2.2 Types of Nano-sensors

The various nano-sensors can be loosely grouped into three broad categories:

- **Physical nano-sensors:** these are used to measure magnitudes such as mass, pressure, force, or displacement. Their working principle is usually based on the fact that the electronic properties of both nano-tubes and nano-ribbons change when these are bent or deformed.
- **Chemical nano-sensors:** these are used to measure magnitudes such as the concentration of a given gas, the presence of a specific type of molecules, or the molecular composition of a substance.
- **Biological nano-sensors:** these are used to monitor bio-molecular processes such as antibody/antigen interactions, DNA interactions, enzymatic interactions or cellular communication processes, among others.

2.3 Nano-machine Development Techniques

In order to develop nano-machines, there are basically three main techniques (i) Top down approach, (ii) Bottom-up approach and (iii) Bio Hybrid Approach [1].

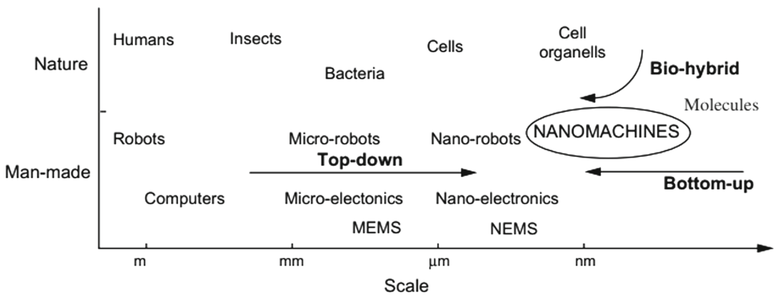

Fig. 2. Approaches for the development of nano-machines [1].

- ***The top-down approach:*** is focused on the development of nano-scale objects by downscaling current existing micro-scale level device components. To achieve this goal, advanced manufacturing techniques, such as electron beam lithography and micro-contact printing, are used. Resulting devices keep the architecture of preexisting micro-scale components such as micro-electronic devices and Micro-Electro-Mechanical Systems (MEMS).
- ***The bottom up approach:*** focused on the design of nano-machines using individual molecules. This approach is nominated as molecular manufacturing. Example: Nano-machines like molecular switches, molecular shuttles, etc.
- ***The bio hybrid approach:*** focused on the design of new nano-machines, also known as biological nano-machines, based on molecular signalling. Example: Bio-nano robots, nano-biosensors, biological storing components etc.

3 Wireless Nano Sensors Networks

3.1 Wireless Nano Sensors Network Architecture

In the previous section, nano-machines have been defined as autonomous units capable of performing simple tasks. The number of tasks that these devices can perform and their range of operation is greatly limited by their size. To facilitate communication between nano-machines, Akyildiz et al. have defined in [3] a new architecture for the nano-sensor-network. They mentioned that a network of nano-sensors should be composed of three types of nodes that can be fixed or mobile, as shown in Fig. 3: The *nano-nodes*, the *nano-routers* and the *nano-micro-interface*, in addition to the *gateway*.

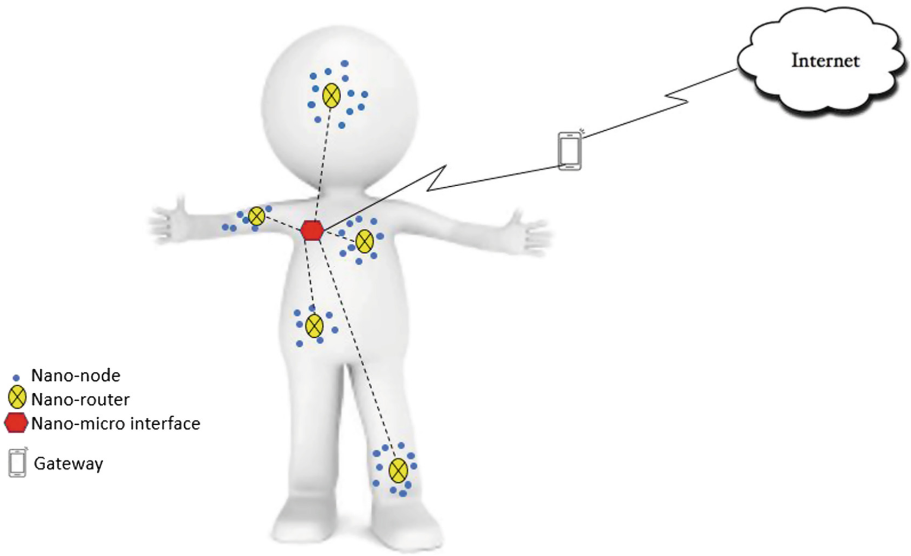

Fig. 3. Wireless nano sensor networks components

- **Nano-nodes:** Nano-nodes are regarded as the smallest and simplest nano-machines which perform various tasks like computation and transmission of the data over short distances and have less memory.
- **Nano-routers:** Nano-routers have large computational power in comparison to nano-nodes and can aggregate and process information coming from nano-nodes. They also control nano-nodes by the exchange of control commands.
- **Nano-micro interface devices:** These devices perform the task of aggregation of information coming from nano-routers and transmit it to the micro-scale and vice versa. They act as hybrid devices to communicate in nano-scale using Nano-communication techniques and also with traditional communication networks using classical network protocols.

- **Gateway:** It enables the remote control of the entire nano-network over the Internet. For example, in health monitoring application, an advanced cellphone can receive the information from a nano-micro interface and forward data to a health-care center.

3.2 Nano-sensor Networks' Communication Paradigms

Since existing conventional communication paradigms can not be applied directly to this domain without taking into account the new constraints of nano-devices, new communication paradigms have been proposed over the past decade. Two main representatives of this field can be cited: (i) *molecular* communications and (ii) *electromagnetic* communications.

Molecular Communication: Molecular communication is defined as the transmission and reception of information encoded in molecules. Molecular communication is a new and interdisciplinary field that spans nano, bio and communication technologies [4]. Molecular communication consists of nano-machines, nano-receptors, carrier molecules, information molecules and the environment in which they operate. Emitters and receivers are biologically and artificially created Bio-Nano-machines that have the ability to emit and capture information molecules. The information data is moved from the sender to the recipient by the carriers. The carriers in this system are molecular motors, hormones or neurotransmitters. Since molecular communication works in the biological system, the information to be transmitted is proteins, ions or DNAs. The environment is the aqueous solution that is inside and between cells.

As illustrated in Fig. 4, the five phases in the operation of molecular communication are as follows:

- **Encoding:** This is the phase in which the bio-nano-source machine, or transmitter codes the information into information molecules that are detected by the bio nano receiving machine.
- **Sending:** This is the phase by which a bio-nano-emitting machine emits these molecules of information into the environment. This is done by untying the information molecules from the sender's bio-nano-machine.
- **Propagation:** Propagation is a common method present in all communication technologies. Propagation is the phase in which information moves from the source to the destination. This is similar for molecular communication where information molecules move from the bio-nano-emitting machine to the bio-nano-machine
- **Reception:** As the word implies, this is the phase in which the bio-nano-receiving machine captures the information molecules that propagate in the bio-nano-environment
- **Decoding:** Encoding and decoding are the most important phases in communication methods. In molecular communication during decoding, the bio nano-receiver machine captures the information molecules and decodes the received molecules into a chemical reaction.

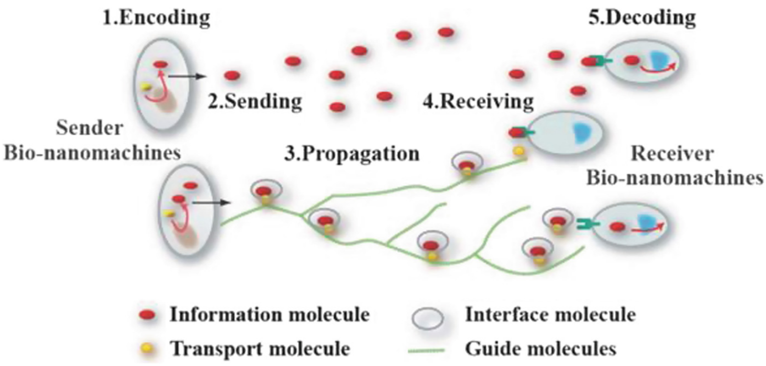

Fig. 4. Molecular communication system [22]

Electromagnetic Communication: The electromagnetic (EM) communication is based on the transmission of information through modulation and demodulation of electromagnetic waves by components that are manufactured by novel nano-materials. Extremely high electromagnetic frequencies (expected in the THz band) are used for communication among nano-devices. This frequency band (0.1–10 THz) can potentially provide very large bandwidths. Recent advancements in molecular and carbon electronics have opened the door to a new generation of electronic nano-components such as nano-batteries, nano-memories [6], logical circuitry in the nano-scale and even nano-antennas [7]. In this paper, we focus on applications based on electromagnetic communications.

4 Nanotechnology for Health-Care Applications

The world of nanotechnology offers fields of application of a crazy diversity. Among the areas in which nanotechnology already plays an important role and will have a decisive role in the future, health is of course in the lead. Different challenges against protocols design are still being investigated with no currently fully developed solutions.

4.1 Communication Challenges

The limited processing and storage capabilities of nano-machines require that **routing design** should take into account the random and dynamic topology of the network inside the body because of the uncontrolled properties of the biological communication medium. Moreover, the routing process should limit to a minimum the collaboration between the nano-machines.

The communication range for IoNT systems should be between $1cm$ and $1m$ for terahertz electromagnetic communication [8]. This implies that the transmission range is very limited, which makes multi-hop communication and routing a critical aspect of nano-networks. In addition, the direction of a communication channel is not deterministic and depends on the speed of the nano-machines inside the body, which can cause a delay in communication. The mobility of nano-machines can be used for routing to reduce delays due to packet propagation but this will require efficient systems for creating and managing multi-hop paths.

Designing a **channel access** procedure is a very difficult task for any wireless technology. Since the WNSN network has a very large number of nano-nodes, it becomes even more difficult. In this context, protocols requiring synchronization between nodes are generally not recommended [9].

In addition, since the most suitable transmission techniques are based on pulse communications, approaches based on carry-over detection strategies, such as carrier-based multiple access (CSMA), can not be applied in the same way because of the absence of a signal to detect.

At the **physical layer level**, since the in-vivo medium contains bio-materials and fluids, e.g., blood, the THz signal could be contaminated. A recent study made by Ahmed et al. in [20] has shown that RBC concentration in the blood widely affects path loss and communication quality. Thus investigating the blood's spreading and absorption spectrum and proposing adequate electromagnetic model for the blood in the THz band is necessary.

4.2 Literature Review of WNSN Communication Protocols

To resolve the above communication challenges and adapt communication protocols to WNSN constraints, several solutions have been recently proposed. In this section, we summarize the key contributions on MAC and routing protocols for WNSN in the electromagnetic communication model.

Greedy energy-harvesting aware and **optimal energy harvesting aware** are two forwarding schemes, based on energy, proposed in [10] for nano-sensors moving uniformly in an environment following human blood directions. In greedy forwarding scheme, the neighbor with the highest energy level is nominated by the greedy energy-harvesting scheme as a relay node. Whereas, the optimal energy-harvesting scheme chooses the node that can maximize the network energy level as a relay node.

A centralized routing framework based on hierarchical clustering architecture is introduced in [11]. The authors introduce a routing framework for WNSNs that uses a hierarchical cluster-based architecture to offload the network operation complexity from the individual nano-sensors towards the cluster heads, or nano-controllers.

Piro et al. Proposed in [12] two routing algorithms along with two MAC protocol for electromagnetic WNSN. In this work, the authors propose and evaluate two routing strategies, specifically the **selective flooding routing** and the **random routing**.

- In the **selective flooding** routing, when a nano-node receives a packet, it broadcasts the message to all the devices within its transmission range. Therefore, a packet generated by a nano-node is propagated into the network.

- In the **random routing** approach, to send a packet to the nano-micro interface, a nano-node selects randomly one neighboring node to forward the data.

In addition to these two routing approaches, Piro et al. introduced two different asynchronous MAC strategies, namely the **transparent-MAC** and **Smart-MAC**:

- In **transparent-MAC**, the packet is simply forwarded from the network layer to the physical layer without executing any kind of control.
- In **Smart-MAC**, the packet received from the upper layer is kept in a queue until delivery to physical layer. Before sending out a packet, the MAC layer starts a handshaking process to find the neighbors of the node. If there is one or more node within its transmission range, it sends the packet to the physical interface. Therefore, if the network layer has not already determined the next-hop, the MAC layer will select it randomly among neighboring nano-nodes. Moreover, if a nano-node haven't any neighbor, the nano-node waits a random back off time, and then it starts the handshaking process to find the nano-nodes in its transmission region.

To evaluate their proposals, Piro et al. implemented the Nano-Sim simulator [13], an NS-3 module to model WNSNs [12] which is currently widely used as a reference simulator.

In [14], a **Probabilistic-Based Broadcasting** for electromagnetic WNSN algorithm is proposed. The algorithm determines the rebroadcast probability by considering the network density. In this way, for low-density nodes, the rebroadcast probability is increased while it is decreased for high density nodes.

5 Our Proposed Communication Architecture

Currently, flooding is the principal protocol used to disseminate data between nano-machines. However, this scheme is inefficient in term of resources usage since it results in bandwidth waste and collision due to excessive messages transmission. Therefore, an urgent challenge for Wireless Nano Sensor Networks is to adapt data dissemination protocols to the energy constraint of the nano-devices while minimizing packet loss ratio, energy consumption, collision and average latency. For this purpose, we present a novel communication architecture to disseminate sensed data inside an artery to an outside controller using a WNSN.

The targeted scenario is a health-monitoring application where multiple nano-devices are deployed in an artery as shown in Fig. 5. Sensing Data are generated by nano-nodes. Data packets are usually sent from nano-nodes (sources) to the nano-micro interface (destination). We assume that, nano-nodes are moving with a constant velocity and following a given direction while the nano-routers and nano-micro interface are stationary nodes. The nano- micro-interface is placed at the middle of the artery. We place the nano-routers in a way that each nano-router has at least one nano-router in its transmission range.

The main idea of our data dissemination scheme is inspired by the geographic routing, which is widely used in VANET [21], WSN [23] and IoT [24] networks.

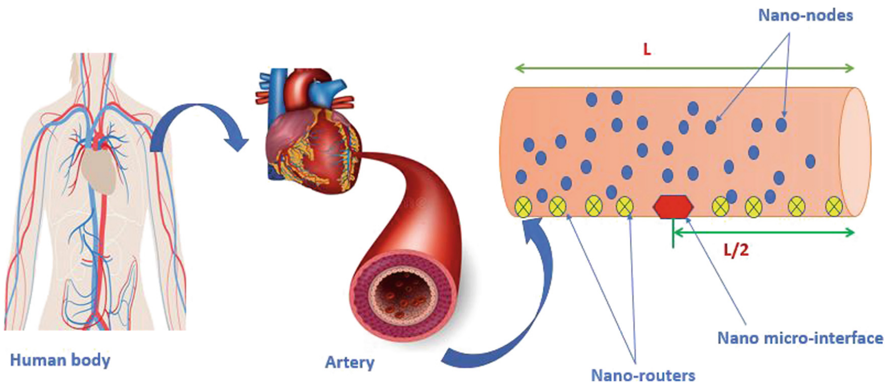

Fig. 5. Proposed communication architecture

As shown in Fig. 6, to avoid energy harvesting the key feature is to reduce the number of relaying nodes (especially relaying nano-nodes) for a given transmission. To that end, we propose to associate each nano-node to one nano-router, called nearest router ($N.R$). The nearest nano-router ($N.R$) is chosen based on its location from the sender nano-node (S). Once reaching the $N.R$, the DATA packet will be forwarded only by nano-routers until it reaches the nano-micro-interface. In other words, a message sent by a nano-router will never be relayed by a nano-node, which save the energy of the nano-nodes.

To reach its nearest nano-router, the sender node (S) selects the best neighbor nano-node ($B.N$) based on its distance to the chosen nearest nano-router ($N.R$). The DATA packet is forwarded from best neighbor to best neighbor until it reaches the nearest nano-router ($N.R$). This scheme guarantees that in each transmission range only one nano-node forwards the DATA packet.

Compared to recent routing protocols proposed in the literature for WNSN (see Sect. 4.2), our approach is clearly more energy efficient due two important conceptual features: First, the association to the nearest router, which guarantees that a minimum number of nanonodes will be involved in the multi-hop transmission to reach the nanorouter. Second, once reaching a nano-router, the

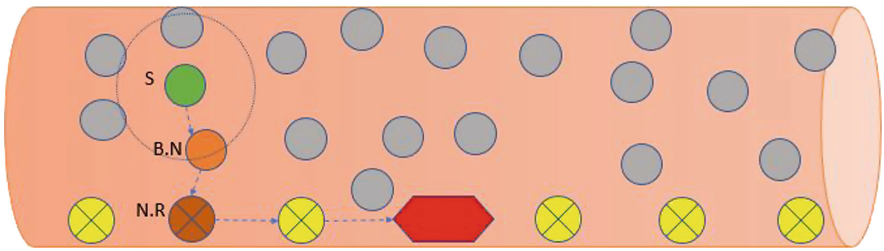

Fig. 6. Principal of our data dissemination algorithm

data is forwarded only between nanorouters, which have more energy resources than the nanonodes. This choice saves nanonodes' energy resources.

Compared to the flooding and the probabilistic schemes, our approach guarantees that only one copy of the packet is forwarded in each transmission range. The probabilistic scheme, even if it introduces a rebroadcast probability parameter to limit the number of copies to be generated, still multiple copies of the packets are forwarded in each transmission range.

Compared to the random routing solution, even if our approach shares with the random solution the advantage of that only one copy of the packet is forwarded in each transmission range, it outperforms the random routing in the choice of the forwarder, which, we recall, is randomly chosen in the random routing. The forwarder selection is obviously more efficient in our solution since it chooses the best neighbor based on its geographic position to the nearest router. This choice reduces hop count and avoids network loops in multi-hop connection, which is the main drawback of the random routing.

Finally, compared to the centralized routing framework, our approach operates in a distributed manner where the routing process is managed by all the nodes in the network, whereas in the centralized approach the life time of the nano-controllers could be a real challenge.

6 Conclusion and Future Scope

In healthcare, the use of nanotechnology is being explored in the fight against diseases such as cancer, glucose etc. That is why, in this paper, we tackle the problem of the applicability of a nano-network to monitor some parameters inside the human body from the data communication perspective. We focus on electromagnetic communication protocols challenges in healthcare applications that must be overcome and we highlight some recent proposals for these communication challenges. Finally, we propose a communication architecture based on a geographic routing approach, to disseminate data between nano-machines while reducing energy consumption. A qualitative comparison to existing solutions highlights the efficiency of our proposal.

As a future work, we plan to carry out a quantitative study to analyze the performance of our approach using simulations.

References

1. Brunetti, F., Akyildiz, I., Blzquez, C.: Nanonetworks: a new communication paradigm. Comput. Netw.: Int. J. Comput. Telecommun. Netw. **52**(12), 2260–2279 (2008)
2. Akyildiz, I., Jornet, J.: Electromagnetic wireless nanosensor networks. Nano Commun. Netw. **1**, 319 (2010)
3. Akyildiz, I., Jornet, J.: The Internet of nano-things. IEEE Wirel. Commun. **17**(6), 58–63 (2010)

4. Moore, M., et al.: A design of a molecular communication system for nanomachines using molecular motors. In: Proceedings of the Fourth Annual IEEE International Conference on Pervasive Computing and Communications (PerCom 2006), March 2006
5. Dragoman, M., Dragoman, D.: Graphene-based quantum electronics. Progress Quantum Electron. **33**(6), 165–214 (2009)
6. Rutherglen, C., Burke, P.: Nanoelectromagnetics: circuit and electromagnetic properties of carbon nanotubes. Small **5**(8), 884–906 (2009)
7. Burke, P., Rutherglen, C., Yu, Z., Burke, P.: Nanotubes and Nanowires. World Scientific (2007)
8. Agoulmine, N., Kim, K., Kim, S., Rim, T., Lee, J.-S., Meyyappan, M.: Enabling communication and cooperation in bio-nanosensor networks: toward innovative healthcare solutions. IEEE Wirel. Commun. **19**(5), 42–51 (2012)
9. Akyildiz, I., Jornet, J.: The Internet of nano-things. IEEE Wireless Commun. **17**(6), 58–63 (2010)
10. Boggia, G., Piro, G., Grieco, L.A.: On the design of an energy harvesting protocol stack for body area nano-networks. Nano Commun. Netw. **6**(2), 74–84 (2014)
11. Akkari, N., Almasri, S., Pierobon, M., Jornet, J.M., Akyildiz, I.: A routing framework for energy harvesting wireless nanosensor networks in the terahertz band. Wirel. Netw. **20**(5), 1169–1183 (2014)
12. Piro, G., Grieco, L.A., Boggia, G., Camarda, P.: Nano-Sim: simulating electromagnetic-based nanonetworks in the network simulator 3. In: Proceedings of The SimuTools, pp. 203–210 (2013)
13. Grieco, L., Boggia, G., Piro, G., Camarda, P.: Simulating wireless nano sensor networks in the NS-3 platform. In: Proceedings of The Workshop on Performance Analysis and Enhancement of Wireless Networks, Barcelona, Spain (2013)
14. Oukhatar, A., Bakhouya, M., Ouadghiri, D.E., Zine-Dine, K.: Probabilistic Based Broadcasting for EM-based Wireless Nanosensor Networks. In: MoMM 2017, 4–6 December 2017
15. Hierold, C., Jungen, A., Stampfer, C., Helbling, T.: Nano electromechanical sensors based on carbon nanotubes. Sens. Actuators. A: Phys. **136**(1), 51–61 (2007)
16. Ji, L., et al.: Multilayer nanoassembly of Sn-nanopillar arrays sandwiched between graphene layers for highcapacity lithium storage. Energy Environ. Sci. **4**(9), 3611–3616 (2011)
17. Stoller, M.D., Park, S., Zhu, Y., An, J., Ruoff, R.S.: Graphene-based ultracapacitors. Nano Lett. **8**(10), 3498–3502 (2008)
18. Wang, Z.L.: Towards self-powered nanosystems: from nanogenerators to nanopiezotronics. Adv. Funct. Mater. **18**(22), 3553–3567 (2008)
19. Yonzon, C.R., Stuart, D.A., Zhang, X., McFarland, A.D., Haynes, C.L., Duyne, R.P.V.: Towards advanced chemical and biological nanosensors-an overview. Talanta **67**(3), 438–448 (2005)
20. Salem, A., Azem, A.M.A.: The effect of RBCs concentration in blood on the wireless communication in Nano-networks in the THz band. Nano Commun. Netw. **18**, 34–43 (2018)
21. Kardi, A., Touati, H.: NDVN : named data for vehicular networking. Int. J. Eng. Res. Technol. IJERT **4**(4) (2015)
22. Nakano, T., Moore, M.J., Wei, F., Vasilakos, A.V., Shuai, J.: Molecular communication and networking: opportunities and challenges. IEEE Trans. Nanobiosci. **11**(2), 135–148 (2012)

23. Aboud, A., Touati, H.: Geographic interest forwarding in NDN-based wireless sensor networks. In: Proceedings of the 13th ACS/IEEE International Conference on Computer Systems and Applications (AICCSA), November 2016
24. Aboud, A., Touati, H., Hnich, B.: Efficient forwarding strategy in a NDN-based Internet of things. Cluster Comput. (2018). https://doi.org/10.1007/s10586-018-2859-7